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Mapping Coastal Hypoxia in the Northern Gulf of Mexico with Ocean Color Imagery

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ABSTRACT

The “dead zone” off the coast of Louisiana in the northern Gulf of Mexico forms every year from mid-April through September and is the second largest hypoxic zone in the world. Ship-based surveys have been conducted each summer since 1985 by the Louisiana Universities Marine Consortium (LUMCON) to map the spatial extent of the bottom hypoxic waters. However, ship sampling is expensive and is not spatially or temporally synoptic. Can we supplement the cruise information by combining surface satellite imagery and 3D hydrodynamic modeling to map the spatial extent of bottom-water hypoxia?

First, we created a 10-year satellite ocean color climatology (monthly composites of relative and absolute partitioned absorption coefficients) for the northern Gulf of Mexico. Next, for each year, we extracted optical properties at hypoxic locations (delineated by the mid-summer ship surveys), to define expected optical conditions of hypoxic waters. Then, for a new image, the observed satellite-derived optical properties are compared to the expected conditions and coupled with a model-derived stratification index (surface-to-bottom density difference) in a four-tiered testing approach, to provide a spatial estimate of possible hypoxic areas. The premise is that correspondence to optical properties observed in past hypoxic events can be used to “predict” where hypoxia is most likely to occur in a new image. We compare hypoxic predictions from this approach with cruise-mapped hypoxic regions. Satellite ocean color imagery can be used to augment ship surveys and delineate areas of expected hypoxic conditions in near-real time, providing coastal managers with a new monitoring tool.

INTRODUCTION

The frequency, extent, and severity of coastal hypoxic events are increasing worldwide due to increasing eutrophication (Diaz and Rosenberg, 2008). Hypoxia occurs when water column oxygen levels drop below 2 mg/l, and these low oxygen levels can potentially impact local fisheries and benthic organisms, with important ecological and economic consequences (Rabalais et al., 2010, and references therein). This “dead zone” off the coast of Louisiana forms every year from mid-April through September and is the second largest hypoxic zone in the world (only the Baltic Sea hypoxic zone is larger). It is generally thought that agricultural fertilization upstream and runoff delivered via the Mississippi-Atchafalaya river basin leads to the increased nutrient loading on the continental shelf, stimulating a phytoplankton bloom (Boesch et al., 2009). However, nonriverine organic matter inputs could also be important (Bianchi and DiMarco, 2008). As the bloom stimulated by this nutrient-rich discharge of the Mississippi and Atchafalaya Rivers sinks to the bottom and decays, oxygen levels are depleted in the process. In addition to the bloom decay, water column stratification is also a required condition for hypoxia development, to prevent mixing with surrounding oxygen-replete waters (Justic et al., 2007).

Typically, ship-based survey cruises are conducted to map the extent of bottom hypoxic waters. Each summer since 1985, monitoring cruises have been conducted by the Louisiana Universities Marine Consortium (LUMCON) to map the spatial extent of the Louisiana hypoxic zone (Table 1). This measurement represents the officially-reported size of the hypoxic zone, which has varied from about 4,000 – 22,000 km², with the maximum size reported in 2002 (LUMCON, 2009). There is currently a national mandate to decrease the size of the hypoxic zone to 5,000 km² by 2015, mostly by a proposed 40% reduction in annual nitrogen discharge into the Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). A monitoring program is required to assess whether these goals are being met. However, ship sampling is expensive and is not spatially or temporally synoptic. *So, the question is, can we combine surface satellite imagery and 3D hydrodynamic modeling to map the spatial extent of bottom-water hypoxia?*

Table 1. Size of coastal Louisiana hypoxic zone.

Year	Hypoxia Size (km²)
1998	12,400
1999	19,750
2000	4,000
2001	20,720
2002	22,000
2003	8,560
2004	15,040
2005	11,840
2006	17,280
2007	20,500
2008	20,720
2009	8,000

OBJECTIVES

Our objectives are to: (1) develop a multi-year data base of satellite-derived optical properties for the northern Gulf of Mexico; (2) from the data base, calculate frequency distributions of the optical properties for hypoxic pixels; (3) estimate water column density structure for the same area and time period using a hydrodynamic model; (4) apply a four-tiered test based on optical and physical properties to estimate likely hypoxic areas; and (5) compare the estimated and observed hypoxia maps.

BACKGROUND

The Naval Research Laboratory (NRL) at the Stennis Space Center (SSC) in Mississippi has developed an Automated Processing System (APS) that ingests and processes AVHRR, SeaWiFS, MODIS, MERIS, and OCM satellite imagery (Martinolich 2006). APS is a powerful, extendable, image-processing tool. It is a complete end-to-end system that includes sensor calibration, atmospheric correction (with near-

infrared correction for coastal waters), image de-striping, and bio-optical inversion. APS incorporates the latest NASA MODIS code and enables us to produce the NASA standard SeaWiFS and MODIS products, as well as Navy-specific products using NRL algorithms. We can readily test and validate new products and easily incorporate new algorithms from other investigators. In addition, as we make modifications to the algorithms, we can easily reprocess many data files (dozens of scenes/day) and compare to previous results. Furthermore, we can automatically extract image data from regions-of-interest to facilitate time-series analyses, and from specific locations for match-ups with *in situ* ship station data. We maintain compatibility with NASA/Goddard algorithms and processing code.

METHODS

To estimate areas of possible hypoxia, we first develop a satellite ocean color climatology, then couple the satellite optical properties with a stratification index derived from a hydrodynamic model, in a four-tiered testing approach. *The premise is that optical properties observed in past hypoxic events can be used to “predict” where hypoxia is likely to occur in a new image (i.e., we compare the*

current conditions to the historical ones). We first compare the relative optical composition, then we examine the absolute optical properties, and finally we assess the water-column stratification and the bathymetry.

Satellite Imagery/Processing

NRL has collected, processed, and archived a 10-year time series of SeaWiFS ocean color imagery (1998-2007) and a 7-year time series of MODIS/Aqua imagery (2003-2009) covering the northern Gulf of Mexico. All imagery was processed with consistent atmospheric correction and bio-optical algorithms using the NRL automated satellite processing system version 3.8.0 (Martinolich and Scardino, 2009) which is consistent with SeaDAS version 5.4 (12gen v5.8.3) and uses the QAA version 4 bio-optical algorithm. An iterative, near-infrared atmospheric correction tuned for coastal waters was applied (Stumpf et al., 2003).

Circulation Modeling

A real-time ocean nowcast/forecast system (ONFS) has been developed at the Naval Research Laboratory (NRL) (Ko et al, 2008). The NRL ONFS provides short-term forecasts of ocean current, temperature, salinity, density, and sea level variation including tides. It is based on the NCOM hydrodynamic model, but has additional components such as data assimilation for sea surface height (SSH) and sea surface temperature (SST) and improved forcing with actual river discharge data. A nested model with 2-km horizontal resolution and 40 vertical layers has been implemented in the northern Gulf of Mexico. The surface-to-bottom (or surface to 100 m in deeper waters) vertical density gradient from this model is used as our stratification index.

Mapping Hypoxia

First, we apply an optical water mass classification (OWMC) system developed at NRL to the imagery (Gould and Arnone, 2003). The OWMC can help identify and track oceanographic features, similar to the approach employed by physical oceanographers using temperature/salinity diagrams. The total absorption coefficient is partitioned into individual absorption components, due to phytoplankton at 443 nm (a_{p443}), sediment/detritus at 443 nm (a_{sd443}), and CDOM at 443 nm (a_{g443}). We then calculate the percent of the total absorption coefficient due to each of the three components, and produce pseudo-color RGB images of the optical patterns, by loading % a_d into the red channel, % a_p into the green channel, and % a_g into the blue channel. So, this three component optical classification scheme also provides a visual representation of the optical variability across a remotely sensed image; areas dominated by relatively high detrital loads appear red in the image, areas of high phytoplankton absorption appear green, and areas of higher CDOM absorption appear blue.

For each year from 1998-2007, using SeaWiFS imagery, we created two-month composite OWMC images covering coastal Louisiana for June and July (SeaWiFS was not operational in June/July 2008 and 2009). Similar composites were created using MODIS/Aqua imagery from 2003-2009, for a separate analysis. Also for each year, we digitized the hypoxia map produced by the LUMCON group. Figure 1 shows an example OWMC image for June/July 2002, the year with the largest measured hypoxic zones (Table 1; 22,000 km²). The cruise-mapped hypoxic area is indicated in red. We then extracted the component absorption percentages at each image pixel and plotted these on a ternary diagram (Fig. 2). The red points on the ternary plot correspond to the red hypoxic pixels in Figure 1, the blue points to non-hypoxic pixels (i.e., all other non-land image pixels).

After repeating this procedure for each of the 10 years, we have 10 ternary diagrams showing the optical characteristics of the hypoxic water masses. We define the small triangles on the ternary plot as “ternels” (ternary elements, analogous to pixels in an image); each ternel represents a 1% change along each of the 3 axes of the ternary diagram. By counting the number of occurrences of each ternel, we created a new ternary plot showing a frequency distribution, to summarize the optical conditions of hypoxic pixels (Figure 3). So, any ternel on the frequency plot can have an integer value from zero (if no hypoxia pixels in any of the 10 years had that particular optical composition) to 10 (if at least one hypoxia pixel in all 10 years had that optical composition.). Thus, the colored ternels in Figure 3 represent a yearly frequency of optical conditions that occurred at hypoxic locations from 1998-2007. The colors on the frequency plot represent the number of years a given combination of absorption percentages (i.e., an individual “ternel” in the ternary diagram) was observed in any hypoxic region. In addition to the frequency plots based on the number of years, similar frequency plots were created based on total number of pixels.

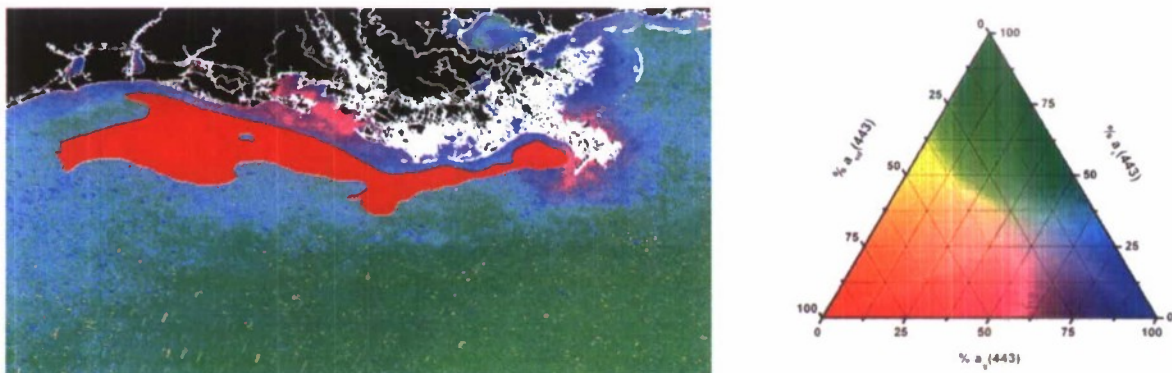


Figure 1. June/July 2002 optical water mass classification. RGB image with % of total absorption at 443nm due to sediment/detritus in the red channel; % due to phytoplankton in green channel, and % due to CDOM in the blue channel. Red blotch field represents the cruise-measured hypoxia distribution. Legend on right corresponds to image pixel colors and indicates optical composition.

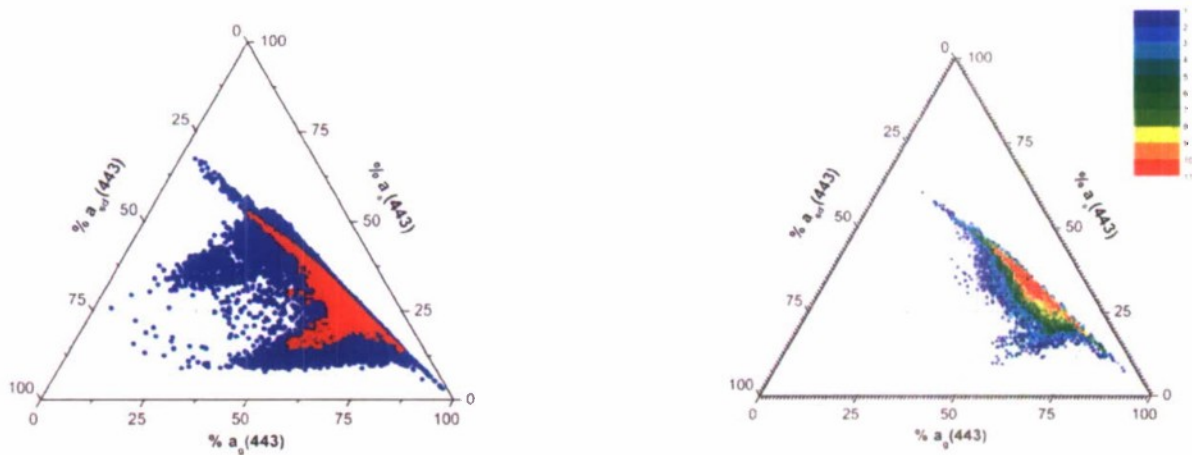


Figure 2. Ternary diagram for June/July 2002 (corresponds to Figure 1). Red points indicate hypoxic pixels, blue points non-hypoxic.

Figure 3. Frequency plot of hypoxic optical conditions, summarizing the 10 individual year ternary plots.

We can now map likely hypoxia regions for any year of interest. First, we need to create the 2-month OWMC composite image for the year(s) of interest, covering the June/July time period. Then, we create a ternary plot for that composite image, and compare it to the frequency ternary. Any pixels that fall in the colored ternels of the 10-year frequency plot can be flagged as likely locations for hypoxic conditions, based on the past results. We can then map the flagged pixels (color coded to represent the frequency) back onto the satellite image to highlight the likely hypoxia locations. The more times (number of years or pixels) that a particular ternel is observed as hypoxic, the more likely that location on the image is to be hypoxic.

However, this OWMC approach only represents changes in the relative optical composition across an image. The optical conditions at the hypoxic pixels are not unique; non-hypoxic pixels can also have the same optical conditions, in terms of the relative composition of the absorbing properties. In other words, some non-hypoxic image pixels will map to the same ternels as the hypoxic pixels, creating “false positives.” To more completely characterize the water masses and reduce the occurrence of false positives, we construct a second test for hypoxia that is based on the actual magnitudes of the absorption coefficients, to further distinguish hypoxic and non-hypoxic pixels. Again, we can create two-month image composites, this time using scaled absorption magnitudes rather than absorption percentages. For each image pixel, the three scaled components at 443nm are calculated as:

$$\text{scaled value} = (a_x - a_{x,\min}) / a_{x,\max-\min} \text{ where}$$

x denotes the component (sediment/detritus, CDOM, or phytoplankton), \min denotes the minimum value observed for that component over the entire 10 year image archive, and $\max-\min$ denotes the range over the 10-year period. We then extract the pixel values from the scaled composite images, and create 3D plots of the scaled absorption coefficients (with axes of a_p443 , $a_{sd}443$, and a_g443 ; not shown), that are analogous to the yearly ternary plots for the absorption percentages, with pixels again denoted as hypoxic or non-hypoxic. Finally, an analogous frequency plot is created as well, from the 10 individual yearly 3D plots. For any year in question, we can then flag the pixels from the composite image that exhibit the same optical conditions with regard to the absolute absorption magnitudes, and map these flagged, color-coded pixels back on to the image, as was done for the absorption percentages.

This represents a two-tiered approach that examines both the absolute and relative optical conditions at hypoxia locations. If a pixel passes both tests (it shows relative *and* absolute optical conditions that are similar to past hypoxic regions), it is more likely to represent a hypoxic location for the year in question. By combining these optical tests with tests for the physical conditions (bathymetry and water column stratification), we have extended our approach to a four-tiered test to further refine our hypoxia prediction. A pixel is flagged as hypoxic if all four of the following criteria are satisfied:

- (1) the relative optical properties match the historical hypoxic properties in at least 8 years and occurred at least 500 times (i.e., in at least 500 pixels over the 10 years);
- (2) the absolute optical properties matched the historical hypoxic properties in at least 8 years and 500 times;
- (3) the water depth is shallower than 50 meters;
- (4) the surface-to-bottom density difference from the model was greater than 1.5 kg/m^3 (i.e., the water column was stratified).

The result is a “now-casting” system that utilizes optical properties derived from satellite ocean color imagery and hydrographic model results to discriminate hypoxic from non-hypoxic water masses, and to predict the likely locations of hypoxia each summer. To test the approach, we can compare our predicted maps with the cruise-based hypoxia maps.

RESULTS

To test the approach, we estimated possible hypoxic pixels in the June/July 2002 OWMC image, and compared these to the actual hypoxia distribution as determined by the cruise sampling. Following extraction of the optical values, comparisons were made with the past hypoxia optical conditions as prescribed by the frequency plots. The four-tiered test described above was then applied, coupling the optical and physical conditions, and the results can be depicted as four separate images. The intersection of these four regions determined the final prediction (Figure 4). Red pixels indicate correctly predicted locations, gray pixels indicate “missed” locations (i.e., the cruise survey observed hypoxia but our approach failed to highlight these areas as likely hypoxic), and yellow pixels indicate “false positives” (i.e., our approach indicated likely hypoxia but the cruise sampling did not observe hypoxia). Note the close correspondence between the estimated and observed hypoxic regions. We performed similar comparisons for the other years.

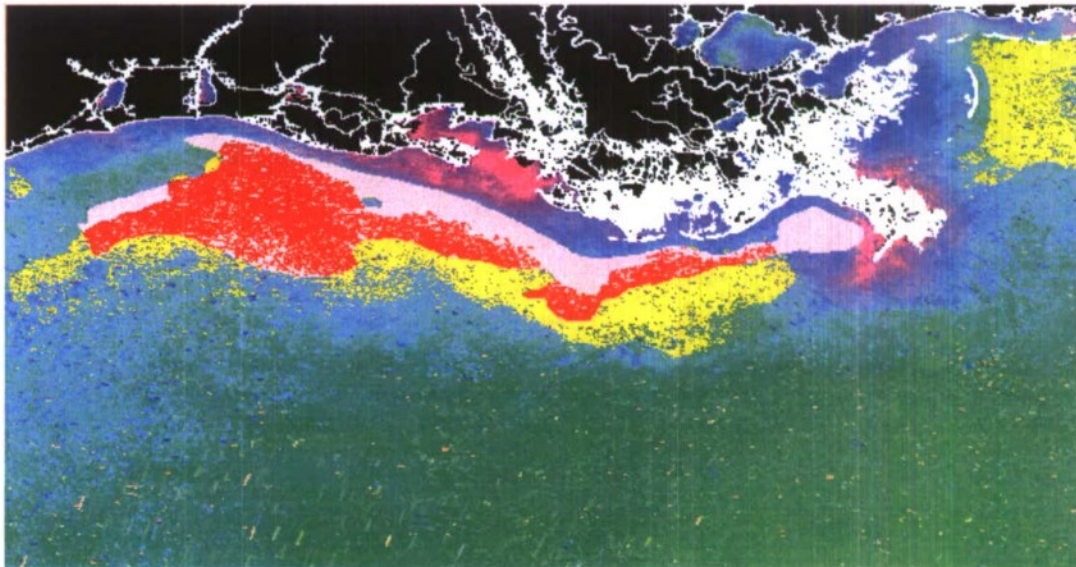


Figure 4. Comparison of estimated and observed hypoxia pixels, June/July 2002. Red: correctly predicted; gray: missed pixels; yellow: incorrectly predicted (false positives). No cruise data was collected east of the Mississippi River delta to validate the predicted hypoxia in that area.

Note the large area of yellow pixels east of the Mississippi River delta. These are better described as “uncharacterized” rather than “false positives”, because this region was not sampled by any of the LUMCON mid-summer surveys. However, some work has indicated that this area experiences sporadic hypoxia, and our approach also indicates that hypoxia is likely there. Plans are underway for future sampling in that area.

We observed that, in general, optical conditions across the coastal area of Louisiana are fairly consistent from year to year. Thus, there would be many false positives for the prediction area based

solely on the optics. The density criterion from the circulation model is therefore a very important factor in determining the size/shape of the hypoxia prediction area.

DISCUSSION AND SUMMARY

This approach to predict hypoxic areas differs from statistical (Turner et al., 2006; Green et al., in preparation) or process-based modeling approaches (Eldridge and Morse, 2008); it only indicates where hypoxia is “most likely” based on comparisons between past optical conditions and current hydrographic (density) conditions. One advantage of this approach is that it doesn’t necessarily require highly accurate satellite optical retrievals, as long as all the entire image time series is processed with consistent atmospheric and bio-optical algorithms. This is because it is a “matching” technique; current conditions are simply compared to past conditions to estimate likely hypoxic areas. The results are not significantly affected if the retrieved absorption coefficients are off somewhat from the “true” values.

Several issues impact how well the estimated hypoxia maps agree with the observed (cruise-based) hypoxic maps. For example, in contrast to the synoptic satellite imagery, the ship sampling is discontinuous and non-synoptic, and the spatial and temporal sampling differences could result in differences between the hypoxia maps. Also, there is a time lag between the initiation of the surface phytoplankton bloom and its subsequent decay, and sinking, and the development of the bottom hypoxia. We use two-month (June/July) image composites that should encompass the bloom initiation/decay and hypoxia development processes, because the time lag between these processes is not known and could be variable. Also, this region is quite cloudy and multi-month composites are frequently needed to obtain cloud-free images for the analyses. The effects of river discharge and tropical storms are important factors impacting the development and deterioration of hypoxia, but they are difficult to quantify. Nutrient additions through river discharge affect the timing and magnitude of the bloom, whereas tropical storm passage disrupts the water column stratification and erodes bottom water hypoxia through mixing with the overlying oxygen-replete waters.

This approach relies on comparison to past hypoxic optical conditions. Thus, if the conditions for a new year (i.e., a year for which an hypoxic estimate is desired) are very different from the optical conditions observed during past years that were used to generate the optical time series and frequency plots, then the predicted hypoxic region for the new year will be off, possibly in size and location. For example, the optical conditions of hypoxic pixels in 2009 were quite different from those observed in previous years (higher a_{s443} absorption; see Fig XX – 2009), so a hypoxia prediction for 2009 based on the previous years would be off. However, this is the same limitation that affects statistical, regression-based approaches. As the optical climatology grows each year, we encompass a greater range of optical conditions, thereby improving estimates.

Why can we successfully use surface optical imagery to represent a bottom hypoxic process? We believe that the validity and demonstrated success of this approach is due to the causative linkage between the bottom hypoxia and the (earlier) surface phytoplankton bloom, which can be detected by satellite. This has been demonstrated indirectly in previous work linking the nitrogen load to the magnitude of the hypoxic zone, as the nutrients stimulate a phytoplankton bloom (Turner et al., 2006). Our approach is more direct, as it relates the surface water optical conditions to the hypoxic size, thereby eliminating a link and a source of error (the coupling between nutrient concentration and bloom magnitude/extent). In addition, recent work (Green et al, in prep) has also demonstrated a linkage between satellite chlorophyll (and SST) and hypoxia size, through multiple regression. Thus,

satellite ocean color imagery can be used to augment ship surveys and delineate areas of expected hypoxic conditions in near-real time, providing coastal managers with a new monitoring tool.

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